The effect of 'running-in' on the tribology and surface morphology of metal-on-metal Birmingham hip resurfacing device in simulator studies

K Vassiliou[1]*, **A P D Elfick**[1,2], **S C Scholes**[1], and **A Unsworth**[1]
[1] Centre for Biomedical Engineering, Durham University, Durham, UK
[2] Institute for Materials and Processes, Edinburgh University, Edinburgh, UK

The manuscript was received on 1 June 2005 and was accepted after revision for publication on 10 November 2005.

DOI: 10.1243/09544119JEIM63

Abstract: It is well documented that hard bearing combinations show a running-in phenomenon *in vitro* and there is also some evidence of this from retrieval studies. In order to investigate this phenomenon, five Birmingham hip resurfacing devices were tested in a hip wear simulator. One of these (joint 1) was also tested in a friction simulator before, during, and after the wear test and surface analysis was conducted throughout portions of the testing. The wear showed the classical running in with the wear rate falling from 1.84 mm^3 per 10^6 cycles for the first 10^6 cycles of testing to 0.24 mm^3 per 10^6 cycles over the final 2×10^6 cycles of testing. The friction tests suggested boundary lubrication initially, but at 1×10^6 cycles a mixed lubrication regime was evident. By 2×10^6 cycles the classical Stribeck curve had formed, indicating a considerable contribution from the fluid film at higher viscosities. This continued to be evident at both 3×10^6 and 5×10^6 cycles. The surface study complements these findings.

Keywords: metal-on-metal resurfacing, wear, running in, lubrication, simulator study

1 INTRODUCTION

Early, small-diameter (less than 32 mm) metal-on-metal hip joints were prone to premature failure [**1**], although some examples are known to have been in place successfully for up to 20 years [**2**, **3**]. This suggests there is a favourable tribological condition in some cases, although not in the majority of cases for the early designs of metal-on-metal joints. New-generation larger-diameter metal-on-metal hip joints have been more successful in the midterm [**4**, **5**] although longer-term clinical results are not yet available.

Hard bearing joints often show a wearing-in period during simulator wear tests [**6–10**], where the initial wear rates are higher than the steady state wear rates. However, the final steady state wear can be more difficult to discern in ceramic-on-ceramic joints, even over 14×10^6 cycles [**9**] owing to the very low values of wear. van Kampen *et al.* [**11**] showed that large-diameter metal-on-metal joints were not initially fully fluid film lubricated and friction tests on other types of metal-on-metal joint have revealed lower friction factors post-wear than initially [**8**], pointing towards more favourable lubrication after wear testing. It has also been noted that the average linear wear rate (microns per year) for retrieved metal-on-metal joints is lower for joints with a longer survivorship, indicating that this wearing-in phase is also likely to occur *in vivo* [**12**]. All this suggests that the articulating surfaces run in during early stages of the wear test, and that this improves the lubrication conditions and hence lowers the wear even further as the tests progress.

**Corresponding author: Centre for Biomedical Engineering, University of Durham Science Laboratories, South Road, Durham DH1 3LE, UK. email: tony.unsworth@durham.ac.uk*

2 MATERIALS AND METHODS

Six Birmingham hip resurfacing (BHR) prostheses were supplied by Midland Medical Technologies, now Smith & Nephew (Bromsgrove). These were all of 50 mm nominal diameter with diametral clearances of 160–210 μm, as shown in Table 1. Diameters were measured post-wear on a Mitutoyo Crysta

Table 1 Diametral clearance for each joint pair tested

Joint identification	Diametral clearance (μm)	Standard deviation (μm)
Joint 1	210	0.17
Joint 2	180	0.77
Joint 3	160	0.21
Joint 4	200	0.23
Joint 5	160	0.40

coordinate-measuring machine using a 12-point least-squares fit for the heads and a nine-point fit for the cups. The mean diameter of each component was calculated from three measurements and was used to determine the clearances.

All friction and wear tests were carried out with bovine serum lubricant (batch 97623; TCS Biosciences, total protein content, 74.4 g/l) filtered through a 0.2 μm filter and diluted to 25 per cent, resulting in a protein concentration of 18.6 g/l. To this was added 0.2 per cent sodium azide and 20 mM ethylenediaminetetraacetic acid to help to resist biodegradation of the lubricant and calcium deposit formation respectively. For the friction study, sodium carboxymethyl cellulose (CMC) was added to the bovine serum lubricant in varying amounts as a viscosity enhancer [**13**], to achieve a range of five viscosities for testing from 0.001 to 0.1 Pa s. The lubricant viscosities were measured at the same shear rate (3000 s^{-1}) as the lubricants in the study by Cooke *et al.* [**13**]. Because of the shear-thinning nature of all these fluids (CMC and bovine serum, as well as synovial fluid) the viscosity will be lower during the actual testing. Previous friction tests in this laboratory with human synovial fluid as a lubricant yielded similar results to those using bovine serum (lowest viscosity tested here) [**14**], although the viscosity of diseased synovial fluid is between the second and third viscosities tested in the present series of experiments. In this study, viscosity-enhanced serum has been used to generate the entire Stribeck plot for a better understanding of the lubrication mechanism.

2.1 Friction study

A single joint (joint 1) was friction tested before the wear test, and after each 10^6 cycles of the wear test, in hip function friction simulator II. This simulator is similar to that described in previous work [**14–16**]. The joint was placed in the friction simulator in an inverted position with respect to the orientation *in vivo*. The cup holder was angled at 33° to simulate the relative positioning *in vivo*, to ensure that the friction was being measured on the contact area from the wear simulator. The maximum and minimum loads during the friction tests were 2000 N and 100 N respectively and the motion was simple harmonic with amplitude 24° and period of oscillation 1.2 s. This is consistent with previous tests performed in this laboratory.

The joint was tested three times with each viscosity of lubricant. The mean and standard deviation were then calculated. In each case the joint pair was cleaned between runs using Gigasept and acetone, according to our standard procedure [**17**].

2.2 Wear study

The components were tested in the Durham hip function wear simulator I, described elsewhere in detail [**18**]. Joints were anatomically positioned, with the cups angled at 33° to simulate the condition *in vivo*. Approximately each 0.5×10^6 cycles the joints were removed, cleaned, and weighed with a protocol closely following ISO 14242-2 [**19**]. The loading profile of the wear simulator followed Paul [**20**] with maximum and minimum loads of 2975 N and 100 N respectively.

2.3 Surface study

The surface roughnesses of the contact region of each component were measured using the Zygo NewView100 non-contacting interference profilometer each 0.5×10^6 cycles up to 3×10^6 cycles and then again at 5×10^6 cycles. Ten measurements were taken on the contact area of each component and various surface parameters were recorded and investigated. Significance was tested by the *t* test.

3 RESULTS

3.1 Friction study

Figure 1 shows the Stribeck curves for joint 1 throughout the wear test. Before wear testing, the joint had a friction factor which was around 0.08, which is much lower than the values of 0.15–0.2 seen for small-diameter metal-on-metal joints [**14**, **21**]. After 1×10^6 cycles, the familiar mixed-lubrication Stribeck curve began to form with the friction factor falling to 0.03 at the highest viscosity. The synovial fluid from a patient with rheumatoid arthritis is around 0.005 Pa s [**13**] measured at a shear rate of 3000 s^{-1}, which corresponds to a Sommerfeld number of 1.7×10^{-9} which lies slightly to the left of the third point on each curve in Fig. 1. At this viscosity, the friction factor within the joint was found

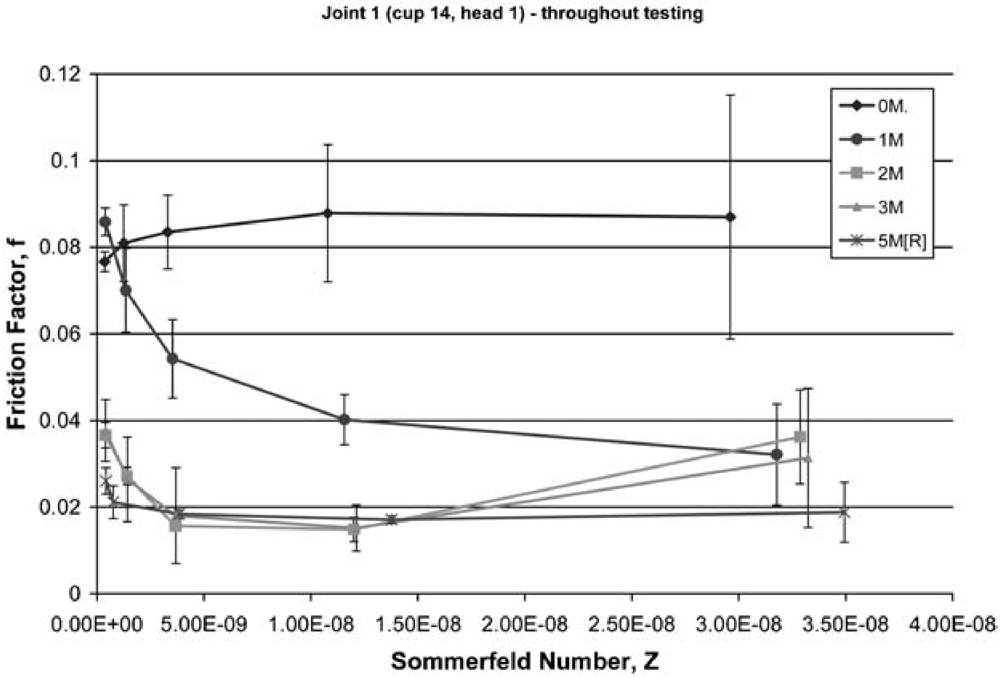

Fig. 1 Stribeck plot for joint 1 throughout wear testing

to be 0.083 initially, falling to around 0.055 at 1×10^6 cycles. At 2×10^6 cycles this fell again to around 0.015 and some fluid-film lubrication behaviour was seen. This seemed to be stable at 3×10^6 and 5×10^6 cycles.

3.2 Wear study

The volume loss on each prosthesis is summarized in Fig. 2 and the wear rates are given in Fig. 3. During the testing, it became apparent that joint 2 was showing much higher wear than the other joints. The rig was checked and no problems were found. However, as part of the checking process, sound emissions were analysed from all five stations and the sound emission from station two was different to the others. At 1.5×10^6 cycles this joint and joint 3 were swapped within the simulator and hence tested in a different station for 0.5×10^6 cycles. Both of these joints continued to follow their previous wear trend over this period and, since no clear evidence was found of station variability, the joints were returned to their original stations within the simulator for the remainder of the test.

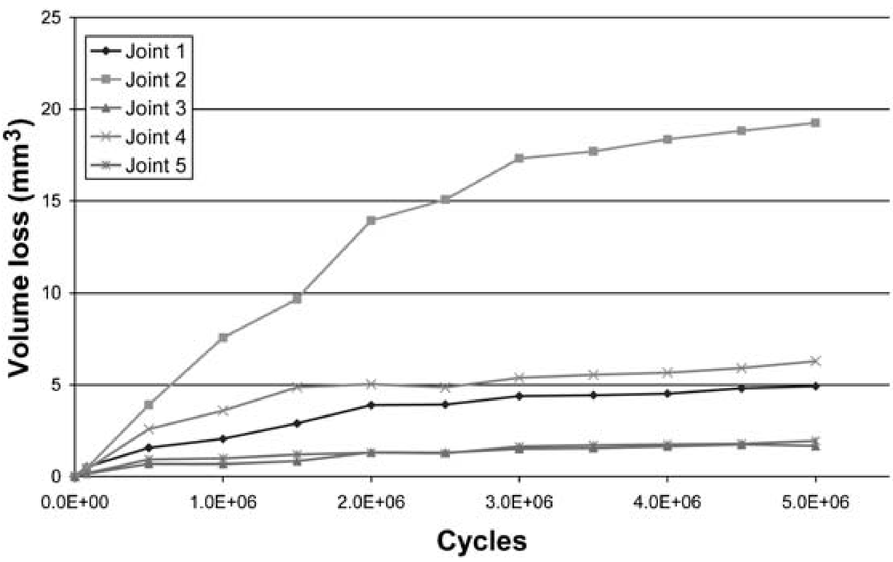

Fig. 2 Volume change on prostheses during wear test

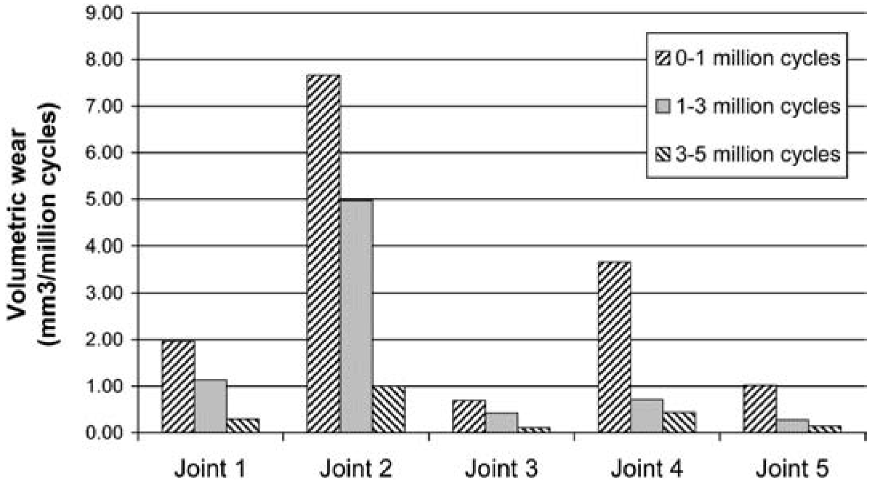

Fig. 3 Wear results for each joint for portions of the wear cycle

For each joint, the wear rates became progressively lower as the test progressed as seen in Fig. 3. Since the wear results for joint 2 were so very different from those for the other four joints, and it was apparent that joint 2 had not 'run in' by 2×10^6 cycles whereas all the others had, the analysis was performed on only joints 1, 3, 4, and 5. Further investigation of joint 2 showed that by 5×10^6 cycles the surfaces had become smooth but, as seen in Table 2, after 5×10^6 cycles joint 2 was the only joint to be significantly rougher than at the start of the test. Clearly something was different about this joint and so in the absence of a full explanation it was felt justified to analyse only the other four joints, which were consistent.

3.3 Surface study

Typical surface images for the components are given in Figs 4 to 6. All images represent an area size of 363 μm × 272 μm and the Z scale is indicated on each image.

Initially the surfaces showed the presence of carbides as an array of protruding features. These were present on all heads and cups and a typical image, as seen in Fig. 4(a). However, as the test progressed, this feature diminished, as seen from Fig. 4(b).

In Figs 5 and 6 the Z scale was maintained at the same level for ease of comparison. The topography of head 1 became progressively smoother throughout the course of testing (Fig. 5). Head 2 also showed a decrease in the carbide features, but surface scratches were more in evidence at 3×10^6 cycles than for head 1 [Figure 6(c)]. The surface smoothed out further by 5×10^6 cycles [Figure 6(d)]. Joint 2 was the joint with the higher wear rates. Cup topography followed a similar trend although to a slightly lesser extent. The initial and final surface data for each component are given in Tables 2 and 3, and statistically significant changes are shown in bold.

A white deposit was seen on some components and this was investigated using scanning electron microscopy (SEM). Elemental analysis revealed the presence of carbon in the deposit, indicating that it was organic in nature and most likely was a protein layer.

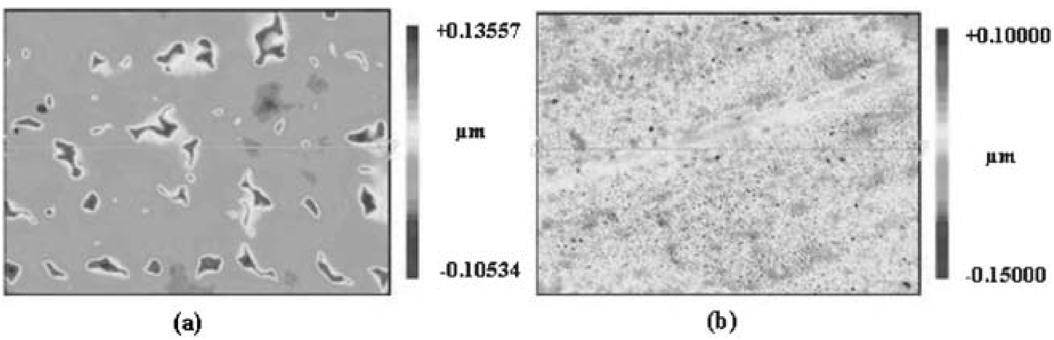

Fig. 4 Surface images of (a) cup 1 (initial) and (b) cup 3 (1×10^6 cycles) showing that carbide feature diminished during wear testing

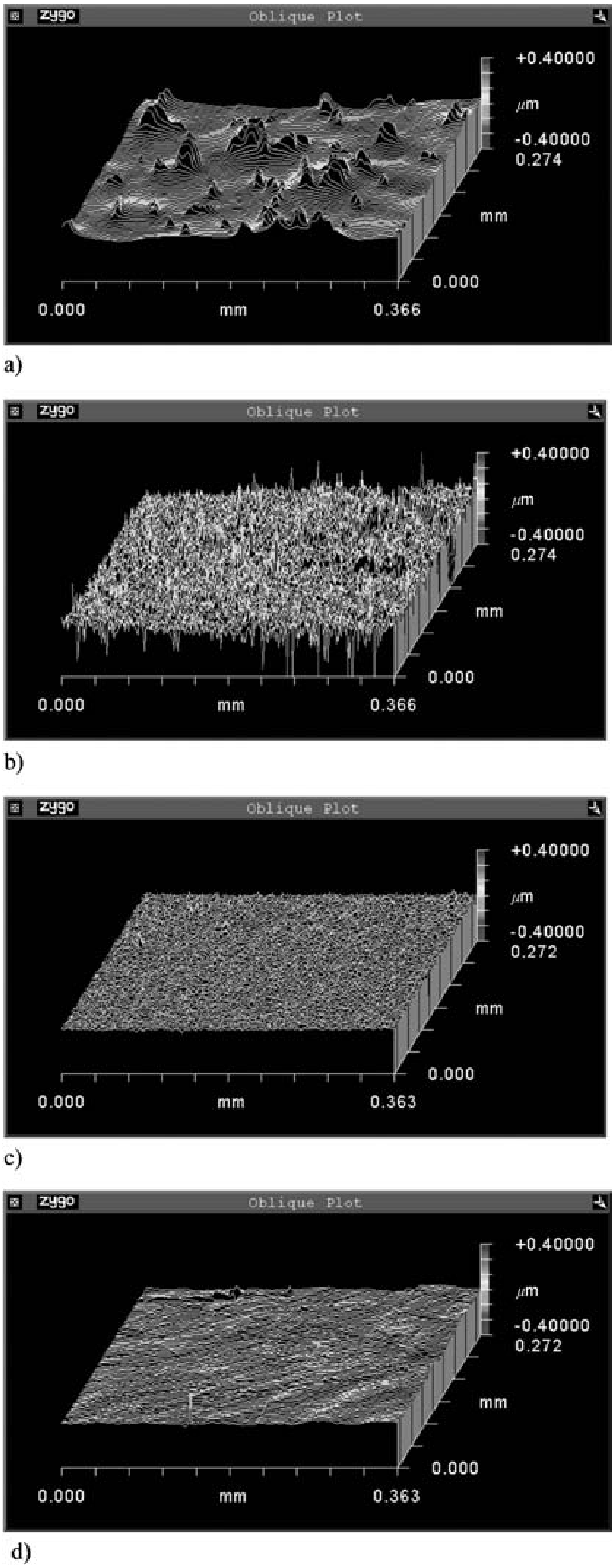

Fig. 5 Surface topography of head 1: (a) initial; (b) after 1×10^6 cycles; (c) after 3×10^6 cycles; (d) after 5×10^6 cycles

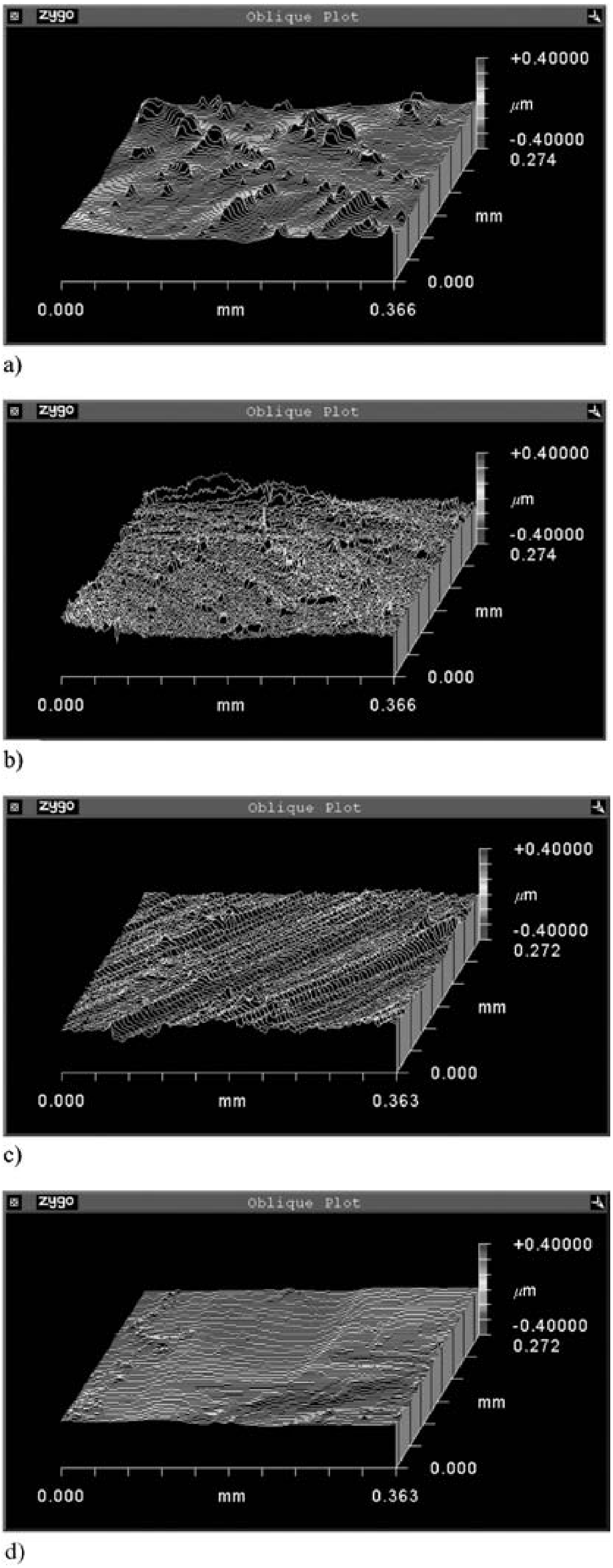

Fig. 6 Surface topography of head 2: (a) initial; (b) after 1×10^6 cycles; (c) after 3×10^6 cycles; (d) after 5×10^6 cycles

Table 2 Average initial and final $S_{r.m.s.}$ values for each individual component; results in bold are statistically significant changes

Component	Initial $S_{r.m.s.}$ (μm)	Final $S_{r.m.s.}$ (μm)
Head 1	0.045 ± 0.004	**0.029 ± 0.017**
Head 2	0.035 ± 0.010	**0.081 ± 0.080**
Head 3	0.040 ± 0.015	0.044 ± 0.041
Head 4	0.054 ± 0.007	0.091 ± 0.092
Head 5	0.042 ± 0.006	**0.114 ± 0.098**
Cup 1	0.058 ± 0.003	0.030 ± 0.004
Cup 2	0.034 ± 0.004	0.046 ± 0.031
Cup 3	0.040 ± 0.011	**0.031 ± 0.007**
Cup 4	0.025 ± 0.005	**0.009 ± 0.001**
Cup 5	0.033 ± 0.002	0.033 ± 0.018

Table 3 Average initial and final S_{sk} values for each individual component; results in bold are statistically significant decreases

Component	Initial S_{sk}	Final S_{sk}
Head 1	1.94 ± 0.21	**−1.19 ± 2.86**
Head 2	1.86 ± 0.42	**−1.20 ± 2.49**
Head 3	1.59 ± 0.53	**−1.16 ± 4.50**
Head 4	1.65 ± 0.32	**−4.91 ± 4.49**
Head 5	1.64 ± 0.29	**−1.24 ± 2.52**
Cup 1	2.03 ± 0.73	1.55 ± 0.83
Cup 2	1.39 ± 0.27	−2.32 ± 14.01
Cup 3	1.80 ± 0.47	**−11.98 ± 6.04**
Cup 4	1.76 ± 0.40	**0.85 ± 0.54**
Cup 5	2.05 ± 0.11	**−8.45 ± 7.15**

4 DISCUSSION

4.1 Wear

The total average wear rate was 0.67 mm^3 per 10^6 cycles. However, the joints showed a higher average wear rate initially [(0–1) × 10^6 cycles] of 1.84 mm^3 per 10^6 cycles, which then reduced to 0.64 mm^3 per 10^6 cycles for (1–3) × 10^6 cycles and reduced further to 0.24 over (3–5) × 10^6 cycles. A higher initial wear rate is common, particularly with metal-on-metal articulations [**8**, **22**, **23**]. It is also not uncommon to see large variations in the wear rates between different components [**8**, **22**, **24**], as seen here with joint 2. The wear rate from this study compares well with simulator results published by other workers [**7**, **22**, **25–27**]. McMinn [**28**] has pointed to laboratory research with differing results from the same type of joint when tested in different simulators, suggesting that direct comparisons can be misleading. It has been suggested that the running-in wear is dependent on the joint clearance [**26**], but in this study there was found to be no correlation between wear rate and clearance, as summarized in Table 4. The wear rates in this simulator study with the BHR are rather lower than reported wear rates from clinical retrieval studies on conventional metal-on-metal total hip replacements, as shown in Table 5. It has still to be discovered whether the wear rates of the BHR on this simulator study will match the wear rates from clinical retrievals of BHR devices.

4.2 Friction and lubrication

The Stribeck plots for the joint tested throughout the wear test are given in Fig. 1. Before wear testing, the joint had an almost constant friction factor in the region of 0.08. This is much lower than the value of 0.18 reported for other metal-on-metal articulations [**14**]. However, as the wear test continued, the shape of the Stribeck curve changed to indicate a more favourable lubrication regime. After 2 × 10^6 cycles the Stribeck curve looked like a classical fluid-film lubrication curve, indicating that at the higher viscosities the joint was operating with a substantial amount of fluid-film lubrication although the presence of a small amount of wear would indicate a small amount of surface to surface contact in conjunction with this mostly fluid-film lubrication.

4.3 Surface topography

Initially the surfaces of all cups and heads clearly showed the presence of carbides protruding from the surface. By 1 × 10^6 cycles these were diminished, a

Table 4 Summary of clearances and wear factors throughout the test for each joint

Joint	Diametral clearance (μm)	Wear rate (mm^3 per 10^6 cycles)			
		(0–1) × 10^6 cycles	(1–3) × 10^6 cycles	(3–5) × 10^6 cycles	Overall wear
1	210	2.05	1.14	0.29	0.93
2	180	7.57	4.98	1.00	4.00
3	160	0.68	0.42	0.10	0.33
4	200	3.59	0.71	0.44	1.08
5	160	0.99	0.27	0.14	0.33
Average (excluding joint 2)		1.84	0.64	0.24	0.67
Correlation		0.26	0.11	0.26	0.16
N		5	5	5	5

Table 5 Clinical wear rates of metal-on-metal joints

Joint type	Wear rate (mm^3/year) Head	Cup	Total	Number of years	Reference
McKee–Farrar	2.04			1–25	[**29**]
Muller	2.97			8–13	[**29**]
McKee–Farrar	2.24	1.4	3.64	8–23	[**30**]

fact supported by the significant reduction in the skewness values of the surfaces. The surfaces became more negatively skewed, which is indicative of diminishing peaks or increasing valleys. The peak-to-valley ratio showed a significant increase on many components. The r.m.s. roughness remained unchanged for some of the components, as seen in Table 2, although some components did show significant changes. However, it should be noted that the roughnesses showed a larger standard deviation at 5×10^6 cycles than at the start of the test, indicating variations in the roughness over the wear area. Looking at this in combination with the skewness, it becomes clear that the roughness was manifest as valleys rather than peaks, which is a more favourable condition for lubrication.

These data were supported by the friction results, which showed a shift towards fluid-film lubrication as the test progressed, and also by the lower wear factor seen in the later stages of testing. Previous workers have seen slightly lower initial roughness values on similar material to that used here [**6**, **26**], which may have an advantageous effect on joint performance.

Joint 2, which showed the highest wear, demonstrated evidence of diminishing features during the course of testing (Fig. 6), but not to such a large extent as the other joints, such as joint 1 (Fig. 5). The evidence of deeper scratching on head 2 supports the higher initial wear rate seen on that joint, while improvement in the surface topography is consistent with the decrease in wear factor.

A whitish deposit was seen on the surface of the joints. SEM X-ray spectral analysis showed that the deposit had a high carbon content, indicating its organic nature. It is likely that this deposit was a layer of denatured protein adhering to the surface. This has been noted before by other workers on explanted McKee–Farrar metal-on-metal joints [**31**].

5 CONCLUSIONS

The wear rates of the BHR devices in this simulator study were rather lower than wear rates of conventional metal-on-metal THR clinical retrievals. There was an initially higher wear rate which decreased with running in of the components. The joint tribology and surface condition both improved with ‘running in’ of the joint, with the surface topography becoming more negatively skewed after the test. Friction factors were very low for metal-on-metal combinations, and the lubrication shifted substantially towards fluid film as the wear test progressed. Surface changes were consistent with the changes seen in friction results and with the reduction in the wear factor as the test progressed. This is the first time that the running-in process has been correlated with improved lubrication conditions as demonstrated by measured Stribeck analysis.

6 ACKNOWLEDGEMENTS

The authors would like to thank Tim Band and Roger Ashton from Smith & Nephew (Bromsgrove) for funding this work and for technical input and Amy Kinbrum for assistance with some of the testing. Mr Arthur Newman provided the technician support.

REFERENCES

1 **Amstutz, H. C.** and **Grigoris, P.** Metal on metal bearings in hip arthropasty. *Clin. Orthop.*, 1996, **329S**, S11–S34.
2 **Schmalzried, T. P., Szuszczewicz, E. S., Akizuki, K. H., Peterson, T. D.,** and **Amstutz, H. C.** Factors correlating with long term survival of McKee–Farrar total hip prostheses. *Clin. Orthop.*, 1996, **329S**, S48–S59.
3 **Jacobsson, S.-A., Djerf, K.,** and **Wahlstrom, O.** 20-year results of McKee–Farrar versus Charnley prostheses. *Clin. Orthop.*, 1996, **329S**, S60–S68.
4 **Amstutz, H. C., Beaule, P. E., Dorey, F. J., Le Duff, M. J., Campbell, P. A.,** and **Gruen, T. A.** Metal-on-metal hybrid surface arthroplasty: two to six-year follow-up study. *J. Bone Jt Surg.*, 2004, **86A**(1), 28–39.
5 **Daniel, J., Pynsent, P. B.,** and **McMinn, D. J. W.** Metal-on-metal resurfacing of the hip in patients under the age of 55 years with osteoarthritis. *J. Bone Jt Surg.*, 2004, **86B**(2), 177–184.
6 **Rieker, C., Schon, R., Konrad, R., Liebentritt, G., Gnepf, P., Shen, M., Roberts, P.,** and **Grigoris, P.**, Influence of the clearance on *in-vitro* tribology of large diameter metal-on-metal articulations pertaining to resurfacing hip implants. *Orthop. Clin. N. Am.*, 2005, **36**, 135–142.
7 **Bowsher, J. G., Nevelos, J. E., Pickard, J.,** and **Shelton, J. C.** Do heat treatments influence the wear of large diameter metal-on-metal hip joints? An *in vitro* study under normal and adverse gait conditions. 49th Meeting of the Orthopaedic

Research Society, New Orleans, Louisiana, USA, 2003, Poster No. 1398.

8 **Scholes, S. C., Green, S. M.,** and **Unsworth, A.** The wear of metal-on-metal total hip prostheses measured in a hip simulator. *Proc. Instn Mech. Engrs, Part H: J. Engineering in Medicine*, 2001, **215**(H6), 523–530.

9 **Clarke, I. C., Good, V. D., Williams, P., Schroeder, D., Anissian, L., Stark, C., Oonishi, H., Schuldies, J.,** and **Gustafson, G.** Ultra-low wear rates for rigid on rigid bearings in total hip replacements. *Proc. Instn Mech. Engrs, Part H: J. Engineering in Medicine*, 2000, **214**(H4), 331–347.

10 **Chan, F. W., Bobym, J. D., Medley, J. B., Krygier, J. J., Yue, S.,** and **Tanzer, M.** Engineering issues and wear performance of metal on metal hip implants. *Clin. Orthop.*, 1996, **333**, 96–107.

11 **van Kampen, M., Scholes, S. C.,** and **Unsworth, A.** The lubrication regime in a metal-on-metal total hip replacement. Proceedings of the International Conference *Engineers and Surgeons – Joined at the Hip*, London, 2002, p. C601/035/2002.

12 **Schmidt, M. B., Weber, H.,** and **Schon, R.** Cobalt chromium molybdenum metal combination for modular hip prostheses. *Clin. Orthop.*, 1996, **329S**, S35–S47.

13 **Cooke, A. F., Dowson, D.,** and **Wright, V.** The rheology of synovial fluid and some potential synthetic lubricants for degenerate synovial joints. *Engng Medicine*, 1978, **7**(2), 66–72.

14 **Scholes, S. C.** and **Unsworth, A.** Comparison of friction and lubrication of different hip prostheses. *Proc. Instn Mech. Engrs, Part H: J. Engineering in Medicine*, 2000, **214**(H1), 49–57.

15 **Unsworth, A., Pearcy, M. J., White, E. F. T.,** and **White, G.** Frictional properties of artificial hip joints. *Engng Medicine*, 1988, **17**(3), 101–104.

16 **Hall, R. M., Unsworth, A., Wroblewski, B. M.,** and **Burgess, I. C.** Frictional characterisation of explanted Charnley hip prostheses. *Wear*, 1994, **175**, 159–166.

17 **Scholes, S. C., Unsworth, A.,** and **Goldsmith, A. A. J.** A frictional study of total hip joint replacements. *Physics Medicine Biol.*, 2000, **45**(12), 3721–3735.

18 **Smith, S. L., Burgess, I. C.,** and **Unsworth, A.** Evaluation of a hip joint simulator. *Proc. Instn Mech. Engrs, Part H: J. Engineering in Medicine*, 1999, **213**, 469–473.

19 ISO 14242-2, Implants for surgery – wear of total hip joint prostheses, Part 2: methods of measurement, 2000 (International Standardization Organization, Geneva).

20 **Paul, J. P.** Forces transmitted by joints in the human body. *Proc. Instn Mech. Engrs, Part J: J. Engineering Tribology*, 1966, **181**(3J), 8–15.

21 **Scholes, S. C., Unsworth, A., Hall, R. M.,** and **Scott, R.** The effects of material combination and lubricant on the friction of total hip prostheses. *Wear*, 2000, **241**(2), 209–213.

22 **Farrar, R.** and **Schmidt, M. B.** The effect of diametral clearance on wear between head and cup for metal-on-metal articulations. 43rd Annual Meeting of the Orthopaedic Research Society, San Francisco, California, USA, 1997, p. 71-12.

23 **Chan, F. W., Bobyn, J., Medley, J. B., Krygier, J. J.,** and **Tanzer, M.** Wear and lubrication of metal-on-metal hip implants. *Clin. Orthop.*, 1999, **369,** 10–24.

24 **Essner, A., Sutton, K.,** and **Wang, A.** Hip simulator wear comparison of metal-on-metal, ceramic-on-ceramic and crosslinked UHMWPE bearings. *Wear*, 2005, **259**, 992–995.

25 **Bowsher, J. G., Hussain, A., Nevelos, J. E.,** and **Shelton, J. C.** The importance of head diameter in minimising metal-on-metal hip wear. 50th Meeting of the Orthopaedic Research Society, San Francisco, California, USA, 2004, Poster No. 1453.

26 **Dowson, D., Hardaker, C., Flett, M.,** and **Isaac, G.** A hip joint simulator study of the performance of metal-on-metal joints. Part I: the role of materials. *J. Arthroplasty*, 2004, **19**(8), Suppl. 3, 118–123.

27 **Dowson, D., Hardaker, C., Flett, M.,** and **Isaac, G.** A hip joint simulator study of the performance of metal-on-metal joints. Part II: design. *J. Arthroplasty*, 2004, **19**(8), Suppl. 3, 124–130.

28 **McMinn, D.** Development of metal/metal hip resurfacing. *Hip Int.*, 2003, **13**, 41–53.

29 **McKellop, H. A., Parl, S. H., Chiesa, R., Doorn, P., Lu, B., Normand, P., Grigoris, P.,** and **Amstutz, H. C.** *In vivo* wear of 3 types of metal-on-metal hip prostheses during 2 decades of use. *Clin. Orthop*, 1996, **329S**, 128–140.

30 **Kothari, M., Bartel, D. L.,** and **Booker, J. F.** Surface geometry of retrieved McKee–Farrar total hip replacements. *Clin. Orthop.*, 1996, **329S**, 141–147.

31 **Wimmer, M. A., Sprecher, C., Hauert, R., Tager, G.,** and **Fischer, A.** Tribochemical reaction on metal-on-metal hip joint bearings: a comparison between *in-vitro* and *in-vivo* results. *Wear*, 2003, **255**(7–12), 1007–1014.

APPENDIX

Notation

BHR	Birmingham hip resurfacing
f	friction factor $= T/rL$
L	normal applied load
r	joint radius
SEM	scanning electron microscopy
$S_{\mathrm{r.m.s}}$	r.m.s. roughness (measured using an area and not a line)
S_{sk}	surface skewness, which is an indication of whether the features of a surface are mostly peaks or valleys (measured using an area and not a line)
T	frictional torque
u	entraining velocity $= (u_{\mathrm{head}} + u_{\mathrm{cup}})/2$
Z	Sommerfeld number $= \eta ur/L$
η	lubricant viscosity